

# Shock-turbulence interaction: Annotated References

*A. C. Buckingham*

**September 15, 1999**

**U.S. Department of Energy**

Lawrence  
Livermore  
National  
Laboratory

## DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Work performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

This report has been reproduced  
directly from the best available copy.

Available to DOE and DOE contractors from the  
Office of Scientific and Technical Information  
P.O. Box 62, Oak Ridge, TN 37831  
Prices available from (423) 576-8401  
<http://apollo.osti.gov/bridge/>

Available to the public from the  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Rd.,  
Springfield, VA 22161  
<http://www.ntis.gov/>

OR

Lawrence Livermore National Laboratory  
Technical Information Department's Digital Library  
<http://www.llnl.gov/tid/Library.html>

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925      Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 1

**TO:** Thomas A. Peyser, Oleg Schilling, Richard A. Ward & Distribution

**FROM:** Alfred C. Buckingham

**SUBJECT:** I. Shock-turbulence interaction: Annotated References (~~Rev. 1~~)

**Precis.** Amplification of turbulence by interaction with a shock wave has been a central issue in compressible fluid dynamics research for over fifty years. While considerable progress has been made in understanding the phenomenon many unresolved questions remain and a consistent theory adequate for a usefully broad range of supersonic – hypersonic flow speeds, constituent gases, and unshocked/shocked thermodynamic state conditions has not emerged. However, very significant amplification of field-averaged turbulence intensity, factors of *6 to 10 or greater*, have been measured in air at near standard atmospheric ambient conditions for low shock Mach numbers. *Intensity* is a convenient and commonly encountered measure of the vigor of turbulence. It is defined as the ratio of the rms fluctuating velocity magnitude to the mean flow speed. It is often expressed as a percentage.

Furthermore it has been observed that the *duration* of the amplified turbulence is *extended* in shock interactions by as much as a factor of 3 over that of unamplified turbulence from the time of its production until it decays to insignificant levels. The *range* of active turbulence similarly increases in direct proportion to the increase in its *duration*. *Range*, as used here, defines the extent of active turbulence; that is the distance measured between where it is produced to where it is essentially exhausted by viscous dissipation into heat. It follows that shock amplified *turbulent mixing*, which scales in proportion to the product of the rms fluctuating speed (or twice the square root of the average turbulence kinetic energy) times the ensemble or temporally averaged (eddy) size, *increases in direct proportion* to the intensity amplification and *persists longer* than that without amplification.

Also experiments suggest (with *favorable code simulation implications*) that amplification occurs predominantly in the *largest scale* motions associated with the *lowest wave numbers* in the dynamic spectrum (*viz. explicitly computable scales*)! In addition, it is observed that *weak* (low intensity) turbulent fields are *amplified much more* by shocks than are *strong* (high intensity) turbulent fields when interacting with shocks of identical strength. In contrast, *high intensity turbulence* tends to have a much *greater distortional influence* on identical strength shock waves than does *low intensity turbulence*. This is particularly evident for weak, (low Mach number) shocks where experiments show that weaker shock waves develop a low frequency, small amplitude, but very evident oscillation in the direction of shock propagation, paired with an equally evident rippling deformation of the shock surface both spanwise and normal to the direction of shock propagation. For very strong shocks, including those experimentally generated at Mach numbers from 10 to 100, the distortional influence is only visibly evident when propagating into “low” ambient gas density (2 or 3 orders of magnitude below standard atmospheric density).

In this, part I, of the present memorandum, I discuss some of the better established experimental findings about the interaction phenomenon and the diagnostic techniques used to detect and measure them. Subsequently, in part II, I will emphasize experimental evidence about the apparent functional dependence of the shock turbulence amplification on initial turbulent intensity, shock strength, and ambient flow state properties. Later memoranda in this series are planned for discussion of theoretical issues and *partial* explanations, scaling, predictive model approximations, and implications drawn from results of selected, published computational studies.

# A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

## MEMORANDUM

Page 2

**Purpose.** This is the first of several, informal technical memos in which I will attempt both a "memory dump" and an update on past and present research on shock wave-turbulence interaction. Despite decades of attention, questions remain about *why*, *how*, and *to what degree* shock interaction with *pre-existing* turbulence amplifies the turbulence, extends its active range and, consequently, has the potential to significantly increase the average level of turbulent component mixing. (As used here, *pre-existing* turbulence is defined as an initial state of fluid dynamic turbulence which has been produced independently and prior to encountering the shock wave). However, much as in the underlying, unresolved problem of fluid dynamic turbulence, a general solution is not sought (even if such an unlikely goal could be considered attainable in a professional lifetime)! Instead, our more limited (*but achievable*) goal is to elevate our understanding of the phenomena by combining scaleable experiments, appropriately sensitive diagnostic techniques, approximating model developments, and analysis. We also hope to attain a reasonable level of confidence in our ability to estimate the influence of the phenomena when subjected to a range of thermo-physical states and flow conditions of programmatic interest. Additionally, this review should help establish a carefully evaluated data base for baseline checks, validation, and refinement of numerical simulation procedures. These tested and experimentally verified procedures may then be applied with some confidence to simulate and predict shock enhanced turbulent mixing incorporating the necessarily full range of driving influences from visible, explicitly computable large scale dynamics down to eddy enhanced molecular diffusion scales when subjected to our unusual and demanding programmatic material, state, and flow conditions. An appreciation of the level of understanding that has been attained about this process in more conventional fluid dynamic environments should be useful and perhaps vital for reaching this goal. These memoranda are intended to assist in developing this appreciation and extending it to fit our special requirements.

**Format.** In discussing preparation of this type of review with Tom Peyser and Oleg Schilling, among others, the suggestion was made that it would be more readable and would provide more stimulation for comments, questions, and constructive criticism if it were divided into "bite-size" portions. The individual memos, issued sequentially in this preliminary form are then to be combined as a series of entries in a loose leaf binder and placed where they can be conveniently reviewed and critiqued. This arrangement appears to be most promising for inspection, review and reference accessibility. It also provides the writer with useful flexibility for subsequent re-arrangement, correction and revision prior to later assembly of the individual memos as parts of a comprehensive final report and/or review paper.

Within each these memos, references will appear cited by author(s) and dates. In this first memo, I have prepared at least the beginning of a general reference list arranged alphabetically by first author. It is intended to serve as a comprehensive reference list for all of the material discussed in the entire group of memos. As such, some of the references listed will not be cited until needed for reference to material introduced in later memos. The list of references will also be supplemented by additional references where necessary in later memos. This first pass at a comprehensive reference list is positioned at the end of this memorandum. The number of selected figures used in this first memorandum are limited to several which best illustrate the more important physical characteristics and influences of shock interaction on turbulent mixing. These will be augmented in part II of this experimental review, by supplemental material and illustrations adapted from the cited literature as well as some more recent data comparisons and theoretical implications from current and on-going research.

# A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

## MEMORANDUM

Page 3

In the intervals between appearance of the individual memos oral presentations on specific topics/questions of particular interest may be useful. You, the reader, will have had a chance to read and review specific topical material of special interest to you, in advance of any scheduled presentation. As a result, your informed contributions and criticisms may contribute substantially to our understanding and, where necessary, revision and more extensive evaluation of the experimental data base and supplemental interpretations and analysis. These oral presentations will also provide a useful forum for discussing the basis of our interpretations, for clarifying significant issues, or for discussion of *classified applications specific to our programmatic interests*.

**Sources.** The information here and that presented in the subsequent memos of what what might be labeled the *unclassified* part of an *A-Program shock wave turbulence interaction review series* is developed from three complementary and clearly interrelated sources. **a.** One is an examination and evaluation of published experimental observations together with identification and characterization of the diagnostic techniques (sensitivity, limitations, and typical systematic error) used to reveal and measure the influence of the interaction on both the turbulence and the shock wave. **b.** Another is data from numerical computations and (conditionally limited) predictive modeling. This source includes some credible published results from the open literature, some results of previous A Division efforts in simulating details of the interaction using unclassified "toy" problem situations, and an unfortunately but understandably quite modest amount of credible data simulation (LES) efforts designed to assist in the analysis of selected interaction experiments. **c.** The third source is *analysis* applied to assist in our search for explanations about dynamics of the interaction phenomena and to assist in bridging the gap between the flow and thermodynamic conditions where consistent experimental evidence has been obtained and physical implications understood and the very different conditions of interest to us here. Here we will augment our discussion using considerations from dimensional analysis, asymptotic limit theory, appropriate scaling arguments, and some application of two well known model approximations: interactive modal analysis and rapid distortion theory.

**General Discussion.** In subsequent memos of the series, I plan to present and discuss some other material that I believe you will find useful for assistance in designing and analyzing experiments; suggesting applications, tests, and perhaps refinements for code/model development; and estimating the level of influence shock wave/turbulence interactions may have on turbulent mixing over a usefully large range of thermodynamic/composition states and flow conditions. Some of the relevant issues that will be discussed in these subsequent memos include, in no intended order of appearance:

- test-to-test conditions, fluid dynamic scaling, dimensional analysis, and similarity;
- approximations, normal mode model analysis, comparison with experiment;
- approximations, rapid distortion theory, comparison with experiment;
- interaction flow field numerical simulations; comparison with experiment;
- interpretations from statistical modeling of interactive shock structure dynamics;
- other topics suggested by your specific questions and interests.

Our discussion in both parts I & II of the experimental description is divided into two categories of experiments: *fixed shock interactions* and *free shock interactions*. The first category includes: (quasi-) stationary shock-wave/turbulent boundary layer interactions, shock-wave/free shear layer interactions, shock-wave/wake interactions, and shock-wave/jet interactions. For the present, we will emphasize shock-wave/boundary layer interaction experiments in this first category. The second category includes moving shock-waves propagating through quasi-stationary turbulent regions. The experiments in this category usually consist of shock tube generated shock-waves interacting, after end-wall reflection, with turbulence generated during their prior, incident passage through the test section.

***Fixed shock interactions.*** In these experiments, an oblique (inclined at a less than normal angle to the incident flow direction) planar or curved two- or three-dimensional shock-wave forms upstream of a two- or three- dimensional solid object fixed to a horizontal plane surface aligned with the incident flow. These experiments are of great value to us, despite the added complications to analysis associated with the stress, heating, and wave reflection accommodated and promoted by the solid surface.

Their enhanced value derives from the relatively long duration (one to several *minutes*) of almost steady (stationary) constant velocity mean flow that we are able to conveniently and reproducibly generate, with strict control over initial conditions, as it passes through a relatively large, diagnostic accessible, test section volume fixed in a laboratory frame of reference. Some obvious advantages are: (a) collection of abundant statistics in the frequency domain over a usefully large spatial range both ahead of and behind the semi-stationary shock position; (b) enhanced ability to maintain precise control of the gas state and mean incident flow parameters as well as to measure and maintain the incident fluctuating (turbulent ) component velocities and their distributions as initial conditions; (c) experimental access for spatial arrays of a variety of complimentary high resolution diagnostics including ultra-thin (high frequency resolving) hot wire anemometry geometric arrays, thin film (high frequency excitation response) surface transient pressure gages, rapid pulsed optical beam schlieren and shadowgraph sequence photography, optical holography and laser doppler velocimetry. In short, this class of experiments is capable of providing high quality statistics defining the turbulence in the frequency domain and information on its spatial evolution, both before and after transition through a semi-stationary shock front. Hour-to- hour and day-to-day reproducibility in the better turbulence wind tunnel test facilities is another important confidence-building feature of this class of experiments when attempting to construct a statistical data base sufficiently accurate and repeatable for resolving exquisitely sensitive turbulence structure functions.

Let's first examine some illustrations. We choose some representative examples from the literature and from previous studies to introduce topics that will be explored more substantially in part II of this memorandum and in later memoranda. To expedite preparation of this introduction, the figures have been placed together at the end of this memo.

We will concentrate here on examples taken directly, or the data adapted from Smits and Muck (1987). The Mach number ranges from 2.25 to about 2.5. In these experiments, constant temperature hot wire anemometry is used for obtaining turbulence data, while mean flow orientation, and magnitudes are obtained from pitot tube pressure rakes in boundary layer and inviscid flow regions above the surface and from flush mounted surface pressure gauges. Quasi-stationary shock, boundary layer, and interaction geometric flow features are recorded through use of shadowgraph photography.

Fig. 1, from Smits and Muck (1987), is a tracing of flow features in the shadowgraph photo images of the flow configurations for shock-boundary layer interaction at a two-dimensional compression corner (wedge) inclined at 8, 16, and 20 degrees (top to bottom in the figure) with respect to the incident horizontal flow-aligned surface. The flow is air at essentially standard atmospheric conditions with a free stream Mach number varying from 2.79 to 2.87 (from largest to smallest wedge angle) and a *unit Reynolds number* of  $6.3 \times 10^7 \text{ m}^{-1}$ . Here the term "unit Reynolds number" refers to that based on a reference scale dimension, in this case, m. At 16 degrees streamline curvature and "free stream" flow deceleration (the inertial region above the outer edge of the boundary layer traced by the open circular symbols) induces incipient (but as yet undetectable) separation of the boundary layer.

At a 20 degree wedge angle boundary layer separation has been realized. The boundary of the separation bubble is traced in the figure as the small arc at the surface to wedge ramp compression corner. Within this bubble the underlying flow recirculates in a clockwise direction relative to the figure. This recirculation in the bubble reverses the flow in an opposite direction to that of the free (non viscous ) flow stream outside the boundary layer above the wall surface.

Streamline curvature distortion at the shock wave (traced as lines A, B, and C. in the sketch) is a maximum for the 20 degree wedge flow. Peak turbulence amplification occurs for the largest scale structures (those extending farthest out in the flow measured, bounded by streamline C, which is displaced from the surface to a distance 0.6 of the total boundary layer thickness. The other streamlines are immersed deeper in the boundary layer. A is displaced from the surface to 0.2 , while B is displaced to 0.4 of the total boundary layer thickness. Curvature distortion is proportional to entropy gain and consequently vorticity generated in interaction with the shock wave. Such distortion of the streamline curvature, direct dilatational compression of the fluid element, and rapid deceleration of the flow due to an adverse (positive ) pressure gradient at the shock wave increase entropy, generate vorticity and add to (amplify) existing turbulence in the shock-boundary layer interaction.

Also in Figure 1, the shock wave may be seen to diffract (separate into a distinct "fan" of weak acoustic waves) near the surface. This apparent break up of the shock front near the wall is common to boundary layer shock interaction. It results from the increasing temperature of the gas and corresponding increase in sound speed plus shear deceleration of the mean flow near the wall. This leads to a rapid decrease in Mach number and eventual attainment of subsonic flow sub layer with no trace of a shockwave near the wall surface.

The unsteady motion of the shock wave and direct generation of vorticity within the fluid element as it transits across the shock wave are also contributors along with acoustic (sound) amplification in exciting the increase in turbulence. Direct translational shock energy is converted to turbulent energy in response to these mechanisms at these more modest Mach numbers. At higher Mach numbers, presumably non-ideal behavior of the gas including dissociation, ionization, and irreversible thermal radiation conceptually contribute, perhaps to this shock-to-turbulence energy transfer, but less has been determined about what happens at these higher Mach numbers.

What is becoming apparent is that there appears to be *no cut off to the amplification of turbulence as Mach Number or shock strength increase to indefinitely high values*. This suggested limitation of influence at higher Mach numbers appears to be the misleading consequence of extending some linear interaction model approximations well beyond their range of validity into the non-linear range of strong shock interaction and response. A counter example is presented later in this memorandum within a subsequent section on free shock interactions.

Amplification of the initial turbulence intensity is shown in profile as functions of the time lapse after shock interaction in Figures 2, 3, and 4. Turbulent intensity is a term used to define the ratio of the rms turbulent excursion velocity relative to the local average streaming velocity of the flow, often expressed as a percentage. *Note particularly that the maximum amplitude increases are apparent along the streamlines in the largest scale structures displaced farthest from the surface. This large scale shock amplification also persists much longer downstream from the initial shock interaction position than does the corresponding amplification in the smaller high frequency spectrum. This preferential low frequency range amplification in boundary layer shock interaction is reproduced in other compression corner boundary layer interaction studies reported here and discussed in more detail in Part II of this memorandum.* Maximum intensity amplification in the Smits and Muck experiments varies from about 1.6 to over 3.6 in these low Mach number (relatively low shock strength) experiments. Attempts to simulate these boundary layer interaction results and perhaps resolve some of the questions about scale influences involved some early work on LES procedures with a primitively tailored sub grid scale model designed to mimic near wall surface influences. The solid lines show the results of both early coarsely meshed and later refined (but still, under-resolved) large eddy simulations from Buckingham (1986) and Buckingham (1991).

These computational results, however unrefined, may help to underline the *overwhelming significance of the largest scale dynamic structures in calculations involving shock-turbulence interactions*. Even the most modestly optimistic forecast suggests that computational studies based on refinements and new developments for LES, and, perhaps, AMR, and PPM procedures possess considerable potential for exploring shock interaction flow conditions and crucial details about the interactions which may be very difficult to observe and measure, experimentally.

These experimental results are also a good example of the strides that have been made in hot wire anemometry as a diagnostic for turbulent flow. For compressible flows the density influence on the mass flux fluctuations (measured indirectly by the fluctuating changes in resistance of the hot wire as it cools by convection) can be accounted for by simultaneous local flow interrogation with pairs of hot wires at different temperatures. Comparison of the paired readings permits discrimination of the effects of temperature/density fluctuations and thereby permits separation of the fluctuating velocity component information from the basic fluctuating mass flux, which drives, through heat transfer, the wire resistance changes, and consequent fluctuating current or voltage signal (depending on how the circuit bias is set) acting through the wire.

Ultra thin (high frequency response), high strength hotwires have been developed and used to measure fluctuations at frequencies ranging up to those of the viscous length scale motions and even smaller. Progress in refinement of this diagnostic technique can best be appreciated by inspection of some well-respected review articles that span several decades of development. The reader's attention is recommended to the sequence of informative reviews by: Kovasznay (1950); Comte-Bellot (1976); Smits, Hayakawa, and K.-C. Muck (1983); and Smits and K.-C. Muck (1984).

During the "fixed" shockwave boundary layer interaction events in stationary mean flow, the shockwave is actually unsteady. It appears to sweep back and forth, and almost as significant, often develops a rippling motion spanwise and in a direction normal to the surface. Chuck Leith has pointed out in discussions on numerous occasions that the spreading shockwave region may represent a departure on the road to adiabatic behavior from that of the classically discontinuous shockwave over which the Rankine-Hugoniot relations guarantee absolutely monotonic increase in entropy.

I examined this from a somewhat different perspective in the hope that it could hold some clues to the interactive exchange processes where energy is transferred from the shock to the turbulence in the fluid element that crosses it. I have not satisfied myself about this but call to your attention some possibly related hints from experimental findings. Bogdonoff and Vas (1961) and Settles, Perkins and Bogdonoff (1981) hint about the upstream influence of unsteady flow inducing shock motion which in turn alters the change in total pressure and decreases the apparent entropy change through the moving shockwave relative to that found in its stationary state. The shockwave pressure jump is reduced and the supersonic drag force on the object supporting the shock is also reduced. This could be of considerable aerodynamic benefit. In a remarkable experiment testing these effects, Calarese and Hankey (1985) showed the reduction induced on a spike tipped hypersonic model where the shock was set into vibrational motion by tip injection of secondary fluid. A confirming note on these influences was provided by a completely unrelated set of Japanese experiments designed to improve corrections to pitot tube measurements of total and static pressure in shocked, supersonic flow. The change in total pressure and reduction in entropy was significant, and repeatably measurable as shown by the work of Shigemi, Koyama, and Aihara (1976).

Careful measurements, using surface pressure gauges in addition to hot wire anemometry indicate no direct correlation between the unsteady motion of the shockwave during interaction and the unsteady motion of the separation "bubble" formed behind the shock at a corner whose inclination with the horizontal is steep enough to induce separation at low (2 to 4) Mach number. Some of the more convincing and informative data on this has been presented by Bogdonoff and Kepler (1955), by Settles, Vas, and Bogdonoff (1976), by Settles, Fitzpatrick and Bogdonoff (1979), and by Settles, Perkins and Bogdonoff (1981).

Unsteadiness within the boundary layer and that of the shockwave during interaction also appear to be unrelated, at least directly, since the frequency of the motions is so disparate. The shockwave oscillations with and without flow separation seem to be in the range of 800 Hz to less than 1.2 - 1.4 kHz while the boundary layer fluctuations are typically 1 to nearly three orders of magnitude higher over the motion scale range. However, since, for example, vortex shedding from the unsteady shockwave (a comparison is made of a semi-permeable sail surface, "luffing" when misaligned in a sailboat steering maneuver) if interacting with the random vortical field within the boundary layer, does so in a nonlinear exchange process, which is not well defined at this state. Several good sources of information on this phenomena include Dolling and Bogdonoff (1982) Dolling and Murphy (1983), Dolling (1985), and Dolling (1993).

Other information on the interaction processes de-emphasizes the role of shock unsteadiness while focusing on the strong out-of-equilibrium state that is generated by the presence of the shockwave on a compression ramp and the restoration of the turbulent dynamic structure and the averaged strain field realignment well downstream of the interaction, but with initiation and restoration boundaries set into unsteady motion even while created in a background of stationary mean flow.

## A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

### MEMORANDUM

Page 8

For a more lucid discussion the reader's attention is directed to the experiments of Andreopoulos and Muck (1987). Rapid distortion theory and approximations for the shockwave boundary layer interactions are used (and will be discussed in a later memo) to help analyze the shockwave boundary layer interactions reported in Debieve and Lacharme (1985) in Debieve, Gouin and Gaviglio (1982) and in Jayaram, Dussauge and Smits (1985). The search for a consistently effective approximate model for the phenomenon continues but good contemporary summaries of the progress that has been made are given by Smits (1988) and in the recent text by Smits and Dussauge (1996).

Another interesting tool for analysis of shock turbulence interaction, perhaps most useful at low Mach numbers, is the normal mode analysis approximation which systematically superimposes contributions of vortical, acoustical and compressional modes when the shock is excited by any of the three modes, independently. The modal analysis procedure, albeit a linear approximation, thereby qualitatively mimics the experimentally confirmed activation of all three modes on excitation during shock interaction by any one of the three independently. The theory and its variants date back, at least, to Moore (1954) and to the progress and developments in shockwave interactions with particular emphasis on acoustical field problems by Ribner (1955), and by Ribner (1987). Actually this is but a small sample of a very large and informative series of papers by Ribner that I will be using in later discussions with you on the modal analysis approximation applied to shock turbulence interactions. An important contribution to the applications of this linear approximation for shockwave turbulence interaction analysis is contained in the paper by Anyiwo and Bushnell (1982) showing some extensions and corrections to algebraic extensions of the theory for polytropic gases presented by McKenzie and Westfall (1968). Useful general summaries of progress made in understanding shock-wave turbulent boundary layer interaction on the basis of average (stochastically insensitive) changes are provided in Green (1970) and in Smits and Dussauge (1996).

Other features of the two dimensional compression corner shock boundary layer interaction data in the same range of flow conditions as those of Smits and Muck (1987) (used the illustrations in this memo) are to be found in Andreopoulos and Muck (1987) where use is made of the same supersonic wind tunnel, model geometry and diagnostics as that of Smits and Muck. Ardonneau (1984) investigated a slightly different range of compression wedge angles but at essentially the same Mach Number with both hot wire anemometry and confirming laser doppler velocimetry as his primary turbulence diagnostics. Complementary work and additional carefully developed turbulence amplification and averaged turbulent boundary layer information including separation phenomena for this class of flows has been described for a slightly lower Mach number range in the experiments of Anyiwo and Bushnell (1982). The influence of Mach number and Reynolds number for a limited range of both parameters have been experimentally investigated by Mateer and Viegas (1979), in the earlier work by Horstman et al (1977) and by Green (1970). The highest Mach number range in wedge generated shock turbulent boundary layer interactions were Russian experiments covering the Mach number range from about 3 to 4 reported in Gol'dfel'd (1985) who used both hot wire anemometry and LDV for the turbulence data.

Before discussing the second category of experiments on free shock turbulence interactions, let me provide you with a few important references to some progress and novel applications of non-intrusive optical diagnostic techniques in LLNL programs. One very relevant example is Guy Dimonte's non-intrusive fast-framing photographic technique on a rapidly moving test chamber in his LEM facility experiments. The diagnostic technique provides vital programmatic information on Rayleigh Taylor bi-material instability growth evolution under the influence of variable acceleration histories for an almost unlimited variety of material and material property combinations. Image capturing presents special problems since in this facility the entire test section containing the test materials is in accelerated motion during the entire (very short) duration of each separate experimental event.

For direct measurement of turbulent spectral structure defining the anisotropic, inhomogeneous turbulent transport and mixing of a passive scalar Albrecht, Robey and Moore (1990) make novel use of the photorefractive properties of BaTiO<sub>3</sub> to create an effective optical temporal filter which separates the nearly stationary background (coherent) laser beam energy from the almost miniscule (of the order of 1 part in 10,000 fractional signal intensity) fluctuating signal component of the beam created as the beam traverses the time and space varying density field generated by turbulent flow. Fourier optics produces simultaneous frequency spectral intensity patterns measuring the turbulent structure for the two orthogonal directions in the plane transverse to the beam axis. This remarkable advance in non-intrusive optical turbulence measurements was successfully demonstrated in LLNL turbulent channel flow shear layer experiments which mapped the anisotropic spectral characteristics of the shear layer in the longitudinal and normal directions as reported in Robey (1990) and in Robey, Albrecht and Moore (1990).

A most informative summary of non-intrusive optical techniques particularly useful for simultaneous measurement of turbulence in two dimensional transverse planes (and with two orthogonal optical beams creating maps of three dimensional flow structure) is provided by Adrian (1986).

**Free shock interactions.** A second category of interest here consists of experiments in which a moving two- or three-dimensional shockwave propagates through a region of previously developed turbulence. Despite the much more limited time available to gather statistics and the limited window access for collecting data on spatial distributions, these experiments more nearly mimic more of the essential flow features of particular concern in our program. Fast framing and streak optical imaging techniques, speckle photography, and a limited amount of hot film anemometry in conjunction with wall mounted transient pressure and heat transfer gauges are used to collect the modest amounts of data generated during the available uncontaminated test period within each distinct event. These events are often supplemented by sequential repetition, under as nearly as possible identical initial and test environment conditions, in order to assemble sufficient statistics for constructing ensemble averages and evolution tendencies.

In Part I of this experimental discussion we will restrict our attention to general discussion and a few examples while in Part II we will examine the cumulative data with special attention to illustrating functional dependence and quantifying the results of shock-wave turbulence interaction in a variety of environments and flow conditions.

Our first illustration, Figure 5, shows a turbulent vapor plume spreading from a laser interaction with a thin aluminum foil target. Vaporization followed interaction with a single 300 J pulsed beam from the PHAROS III (1.06  $\mu\text{m}$ ) laser at the Naval Research Laboratory.

## A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

MEMORANDUM

Page 10

A second PHAROS III beam pulse interacting with a second foil target creates both a plume and (on the reverse side of the foil) in reaction to the ablation, a high Mach Number (approximately Mach 100) cylindrical shock. This shock, in turn, propagates into the turbulent plume created by the first beam. The power spectral density is measured with phase-contrast microscopy shuttered at 600 picosec. The experiments were designed and conducted by Grun et al. (1992). This is probably the first direct evidence obtained in controlled experiments that turbulence is amplified substantially even when driven by very strong shocks in the hypersonic range. The Al vapor plume expands and fills a very low density (5 torr) background of Nitrogen gas. The shock front is seen to be completely distorted and the turbulence altered (amplified) significantly during shock passage. LES was applied to assist in the analysis of the process, Buckingham and Grun (1993a) and Buckingham and Grun (1993b). The results will be discussed in context with other experiments under different flow conditions in Part II of this memorandum.

Honkan and Andreopoulos (1992) used hot wire anemometry in the shock tube reshock studies of grid generated turbulence to produce the initial turbulent flow (open symbols in Figs. 6 and 7. The reshock phase (filled symbols) is seen to significantly amplify the original energy over about the production range and beginning of the inertial range of the measured turbulence energy spectrum for three different *mesh Reynolds numbers* (where the characteristic Reynolds number length scale is the mesh opening). Figure 6 shows results for Reynolds number 35,000, while figure 7 shows results for Reynolds numbers 58,000 on the left and 74,000 on the right. *In all of these results the larger scale, computable dynamic structures are significantly amplified, while the high wave number inertial range is essentially insensitive to shock amplification.* This, of course, has considerable significance for the development, test, and use of numerical techniques to help analyze and predict this phenomenon.

Fig. 8 illustrates directly this preferential amplification of the largest scale dynamic structures, with a plot of the log initial turbulence and shocked turbulence intensity vs. log of the wave number for one dimensional (streamwise) spectra. The bottom graph in Figure 8. Shows the ratio of shocked to unshocked intensity (amplification ratio) as a function of wave numbers. Both plots indicate that sensible amplification drops off at the low wave number beginning of the inertial range, and well before the sparse statistics gathered bar further (higher spatial frequency) resolution.

Fig. 9 from these same experiments illustrates that the rate of decay of the turbulence behind the generation region is substantially decreased for shock wave amplified turbulence in comparison to the original mesh generated turbulence. The bottom figure helps to uncover an additional perspective about the shock influence on turbulence. Here the intensity amplification ratio for shocked vs. unshocked turbulence is plotted with distance behind the generation position. Amplification is strictly monotone increasing with distance! Part of this steep increase in amplification is simply a manifestation of the observation we have already discussed. That is lower intensity turbulence (near the limit of its decay and dissipation into heat is amplified much more by shock influences than is more vigorous turbulence. Perhaps the more important suggestion from these results as well as those from the shock wave boundary layer studies is that *shock wave amplification acts to promote and preserve the significant turbulent intensity well beyond the range where the unshocked turbulence dissipates to inconsequential levels.* In another sense, *the reshock phase in turbulence amplification extends the range of the vigorous turbulence much further than that of unshocked turbulence and thereby potentially extends the effective turbulent mixing range!*

# A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

## MEMORANDUM

Page 11

Additional information will be developed in Part II on functional dependence from the foregoing examples and from the *speckle photography optical diagnostics* applied by Keller and Merzkirch (1990) in shock tube reshock amplification of mesh generated turbulence experiments, as well as the shock tube reshock amplification experiments of Troler and Duffy, 1985 and those of Hartung and Duffy, 1986, where the non-uniform, initial turbulence is generated from the trailing turbulent boundary layer swept into the wake of the advancing shock before reflection. The latter cases also used hot wire anemometry to measure the turbulence and its amplification over a range of Reynolds numbers.

Possibly the most instructive and accessible reference to the speckle photographic diagnostic technique is provided by Adrian (1991). In part II we will also summarize with LES results used in analysis of the Hesselink (1977) experiments from the innovative LLNL code work of Rotman (1991) as well as supplementary discussion of the development and application of modern 3 dimensional non intrusive imaging techniques from Hesselink (1988).

Prior to leaving this introductory discussion it seems appropriate to introduce some other references may (and probably should) influence our thinking about the source and influence of shock waves on turbulence. A revised view of shock wave boundary conditions for deforming, moving shocks may be formed from the work of M. Bonnet (1988), of Lele (1994) and the shock dynamic differential geometry research of Emanuel (1976). Useful numerical techniques and results that will be discussed later includes the influential suggestions from work of Zang, Kopriva, and Hussaini (1983) and of Zang, Hussaini, and Bushnell (1984).

The Monte-Carlo shock structure computations and theoretical model analysis used to isolate and identify some of the significant but (heretofore) experimentally undetectable dynamics influencing shock turbulence interaction will also be the subject of future memoranda. Reference here is to the pioneering work on molecular shock structure in the numerical studies by Bird (1967) and some rudimentary turbulent Monte-Carlo studies by Buckingham (1991) and Buckingham (1990). The functional dependence of the interaction on flow field variables and shock wave strength will be illustrated based on results exploiting analytical series expansions stimulated by the (incomplete, but perceptively suggestive) classic results of Mott-Smith (1951) and the seminal and typically physically insightful study of Taylor (1910).

### References

- R. J. Adrian (1986), "Multi-point Optical Measurements of Simultaneous Vectors in Unsteady Flow – A Review." *Int. J. Heat Fluid Flow*, 7, 127-145.
- R. J. Adrian (1991), "Particle Imaging Techniques for Experimental Fluid Mechanics" *Ann. Rev. Fluid Mech.* 23, eds. J. L. Lumley, M. Van Dyke, H. Reed, Ann Rev. Inc., Palo Alto, 261-304.
- G. F. Albrecht, H. F. Robey, and T. R. Moore (1990), "Optical Technique for the Measurement of Turbulent Spectra Using the Photorefractive Properties of BaTiO<sub>3</sub> , *Appl. Phys. Lett.*, 57, (9), 864 - 866.
- J. Andreopoulos & K. C. Muck (1987), "Some New Aspects of the Shock Wave Boundary Layer Interaction in Compression Ramp Flows," *J. of Fluid Mech*, 180, 405-428.
- P.L. Ardonceau (1984), "The Structure of Turbulence in a Supersonic Shock-Wave/Boundary Layer Interaction," *AIAA J.*, 22, (9), 1254-1262.
- J. C. Anyiwo and D. M. Bushnell (1982), "Turbulence Amplification in Shock Wave Boundary Layer Interactions". *AIAA J.*, 20, 893-899.
- G. K. Batchelor and I. Proudman (1954), "The Effect of Rapid Distortion of a Fluid in Turbulent Motion", *Q. Journ. Mech. Appl. Math.* 7, 83.
- G. A. Bird (1967), "The Velocity Distribution Function Within a Shock Wave", *J. Fluid Mech*, 30, 479.
- S. M. Bogdonoff & C. E. Kepler (1955), "Separation of a Supersonic Turbulent Boundary Layer", *J. Aero. Sci.*, 22, (6), 414-424.
- M. Bonnet, S. Gauthier, B. Sitt, & P. Spitz (1988a), "Turbulent Jump Relations in the Interaction of a Shock Wave with a Turbulent Region", *Advances in Compressible Turbulent Mixing*, eds. W. P. Dannevik, A. C. Buckingham, C. E. Leith, U. S. Government Printing Office: 1992-687-052/P9000, 387-394.
- M. Bonnet, S. Gauthier, & P. Spitz (1988b), "Numerical Simulations with a 'k-e' Mixing Model in the Presence of Shock Waves", *Advances in Compressible Turbulent Mixing*, eds., W. P. Dannevik, A. C. Buckingham, C. E. Leith, U.S. Government Printing Office: 1992-687-052/P9000, 397-406.
- A. C. Buckingham (1986), "Pseudospectral Computations Illustrating Shock wave Turbulence Amplification in Viscous Flow". *Numerical Methods in Laminar and Turbulent Flow, Part 2*. ed. C. E. Taylor, Pineridge Press, Swansea, UK. 963 - 971.

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925      Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 13

A. C. Buckingham (1989), "Numerical Studies of Shock Wave Structure Sensitivity to Interactions with Turbulent Fields", *Numerical Methods in Laminar and Turbulent Flow*, VI, eds. C. E. Taylor, P. Gresho, R. L. Sani, J. Hauser, Pineridge Press, Swansea, UK, 805-814.

A. C. Buckingham (1990), "Interactive Shock Structure Response to Passage Through Turbulence", *AIAA Paper 90-1642, AIAA 21st Fluid and Plasma Dynamics Conf. Seattle*, WA, 9 - 13 July.

A. C. Buckingham (1991), "Shock wave Considerations for Sub-Grid Closure Modeling in Turbulent Large Eddy Simulations", *Numerical Methods in Laminar and Turbulent Flow*, VII, (2) eds. C. E. Taylor, J.H. Chinn, G. M. Homsy, Pineridge Press, Swansea, UK. 897-905.

A. C. Buckingham & J. Grun (1993a), "Sub-Grid Scale Modeling for Large-Eddy Simulations in Analysis of Shock-Turbulence Interactions", *Numerical Methods in Laminar and Turbulent Flow*, VIII, eds. C. E. Taylor, R. L. Sani, Pineridge Press, Swansea UK.

A. C. Buckingham & J. Grun (1993b), "Numerical Simulations and Experiments on Physics of High Mach Number Shock wave - Turbulent Flow Interactions, *Proc. 4th International Workshop on the Physics of Compressible Turbulent Mixing*, eds. P. Linden and D. Youngs, Cambridge University.

B.W. Calarese & W. L. Hankey (1985), "Modes of Shock-Wave Oscillations on Spike-Tipped Bodies," *AIAA J.*, 23, (2), 185-192.

G. F. Chapline & T. A. Weaver (1979), "Structure of Relativistic Shock Waves in Simple Gases" *Phys. Fluids*, 22, (10), 1884-1889.

G. Comte-Bellot (1976), "Hot-Wire Anemometry" *Ann. Rev. Fluid Mech.* 8, eds. M. Van Dyke, W. G. Vincenti, J. V. Wehausen, Ann. Rev. Inc., Palo Alto, 209-231.

J.- F. Debieve, H. Gouin, & J. Gaviglio (1982), "Evolution of the Reynolds Stress Tensor in a Shock Wave-Turbulence Interaction," *Indian J. Technology*, 20, (3), 90-97

J.- F. Debieve & T.- P. Lacharme (1985), "A Shock-Wave/Free Turbulence Interaction," *Turbulent Shear Layer/Shock Wave Interactions, IUTAM Symposium Proc.*, ed J. Delery, Palaiseau, France, Sept., 394-403.

J. - F. Debieve (1986), "Interaction Entre Une Turbulence Libre et Une Onde de Choc", *Universite d'Aix Marseille, Institut Mecanique Statistique de la Turbulence, IMST, Rept. ONERA/IMST No. 20.352/SAT/2/CDC.*

D. S. Dolling and S. M. Bogdonoff (1982), "Blunt Fin-Induced Shock Wave Turbulent Boundary Layer Interaction", *AIAA J.* 20, 1674-1680.

D. S. Dolling and M. T. Murphy (1983), "Unsteadiness of the Separation Shock Wave Structure in a Supersonic Compressible Ramp Flowfield". *AIAA J.* 21, 1628-1634

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 14

D. S. Dolling (1985), "Unsteadiness of Shock Wave – Induced Turbulent Boundary Layer Separation – A Review", *IUTAM Symposium on Turbulent Shear Layer/Shock Wave Interaction* ed. J. Delery, Palaiseau, France, Sept.

D. S. Dolling (1993), "Fluctuating Loads in Shock Wave/Boundary Layer Interaction: Tutorial and Update" *AIAA Paper 93-0284*.

G. Emanuel and M.-S. Liu (1988), "Shock Wave Derivatives", *Phys. Fluids* 31, (12), 3625-3633.

M. A. Gol'dfel'd (1985), "The Structure of a Supersonic Turbulent Boundary Layer in its Interaction with a Shock Wave", translated from *Izvestiya Akademii Nauk SSSR, Mekhanika Zhidkosti Gaza* 5, 75-82.

J. E. Green (1970), "Interaction between Shock Waves and Turbulent Boundary Layers", *Prog. In Aerospace Sci.*, 11, AIAA Publ. NY, Washington DC, 235–340.

J. Grun, C. K. Manka, B. H. Ripin, A. C. Buckingham, J. Resnick, and H. R. Burris (1992), "Enhancement of Turbulence by a High Mach Number Shock", *Bull. APS*, 37, (6), 1478.

L. C. Hartung and R. E. Duffy (1986), "Effects of Pressure on Turbulence in Shock Induced Flows", *AIAA Paper 86-0127*, *AIAA 24th Aerospace Sciences Meeting, Reno, NV*.

L. Hesselink (1977), "An Experimental Investigation of the Propagation of Weak Shock Waves Through a Random Medium", *Shock Tube and Shock Wave Research*, eds. Ahlborn, Hertzberg, Russel, pp. 82-90.

L. Hesselink (1988), "Digital Image Processing in Flow Visualization," *Ann. Rev. Fluid Mech.* 20, eds. J. L. Lumley, M. Van Dyke, H. L. Reed, Ann. Rev. Inc., Palo Alto, 421-485.

A. Honkan and J. Andreopoulos (1992), "Rapid Compression of Grid-Generated Turbulence by a Moving Shock Wave", *Phys. Fluids A* 4, (11), 2562 – 2572.

C. C. Horstman, G. S. Settles, I. E. Vas, S. M. Bogdonoff, and C. M. Hung (1977), "Reynolds Number Effects on Shock Wave Turbulent Boundary Layer Interactions", *AIAA J.*, 15, 1152-1158.

J. C. R. Hunt (1973), "A Theory of Turbulent Flow Around Two-Dimensional Bluff Bodies", *J. Fluid Mech.* 61, 625 – 706.

M. Y. Hussaini, F. Collier, & D. M. Bushnell (1985), "Turbulence Alteration Due to Shock Motion", *Turbulent Shear Layer/Shock Wave Interactions, IUTAM Symp. Palaiseau, France*, ed. J. Delery, Springer Verlag, Berlin, Heidelberg, 371 – 381.

T. L. Jackson, M. Y. Hussaini, and H. S. Ribner (1992), "Shock Turbulence Interactions in a Reacting Flow", *ICASE Rept 92 -20*, NASA Langley Res. Ctr., Hampton, VA

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 15

M. Jayaram, J.-P. Dussauge, and A. J. Smits, (1985), "Analysis of a Rapidly Distorted, Supersonic, Turbulent Boundary Layer", *Fifth Symposium on Turbulent Shear Flows*, Cornell University, Ithaca, NY. 1-8.

J. Keller and W. Merzkirch (1990), "Interaction of a Normal Shock Wave with a Compressible Turbulent Flow", *Expts. In Fluids* 8, 241 -248.

L. S. G. Kovasznay (1950), "The Hot Wire Anemometer in Supersonic Flow", *J. Aero. Sci.*, 17, 565.

L. S. G. Kovasznay (1953), "Turbulence in Supersonic Flow", *J. Aero. Sci.* 20, (10) 659 - 682.

M. J. Lee, U. Piomelli, and W. C. Reynolds (1986), "Useful Formulas in the Rapid Distortion Theory of Homogeneous Turbulence", *Phys. Fluids* 29, (10), 3471-3474.

S. Lee, S. K. Lele, & P. Moin (1991), "Eddy Shocklets in Decaying Compressible Turbulence", *Phys. Fluids A* 3, (4), 657-664.

S. K. Lele (1992), "Shock-Jump Relations in a Turbulent Flow", *Phys. Fluids A* 4 (12), 2900 - 2905.

S. K. Lele (1994), "Compressibility Effects on Turbulence", *Ann. Rev. Fluid Mech.* 26, eds. J. L. Lumley, M. Van Dyke, H. L. Reed, Ann. Rev. Inc., Palo Alto, pp. 235-244.

G. G. Mateer and J. R. Viegas, (1979), "Effect of Mach and Reynolds Numbers on Normal Shock-Wave/Turbulent Boundary Layer Interaction", *AIAA Paper 79-1502*, *AIAA 12th Fluid and Plasma Dynamics Conf.*, Williamsburg, VA.

J. F. McKenzie and K. O. Westphal (1968), "Interaction of Linear Waves with Oblique Shock Waves", *Phys. of Fluids, II*, (11), pp. 2350 - 2362.

F. K. Moore (1954), "Unsteady Oblique Interaction of a Shock Wave With a Plane Disturbance", *National Advisory Committee for Aeronautics*, *NACA TR-1165*.

H. M. Mott-Smith (1951), "The Solution of the Boltzmann Equation for a Shock Wave", *Phys. Rev.*, 82, p. 885.

L. Prandtl (1933), *Nat'l. Advis. Comm. Aeron.*, *NACA Tech Memo TM 726*, Washington, D. C.

H. S. Ribner and M. Tucker (1952), "Structure of Turbulence in a Contracting Stream", *Natl. Advis. Comm. For Aeron.*, *NACA TN 2606*, Washington D. C.

H. S. Ribner and F. K. Moore (1953), "Unsteady Interaction of Disturbances with a Shock Wave With Applications to Turbulence and Noise", *Proc. 1953 Ht. Trans. & Fluid Mech. Inst.*, 45-55.

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 16

H. S. Ribner (1954), "Convection of a Pattern of Vorticity Through a Shock Wave", *Natl. Advis. Comm. For Aeron., NACA TR 1164*, Washington D. C.

H. S. Ribner (1955), "Shock Turbulence Interaction and the Generation of Noise", *National Advisory Committee for Aeronautics, NACA TR-1233*.

H. S. Ribner (1987), "Spectra of Noise and Amplified Turbulence Emanating from Shock-Turbulence Interaction", *AIAA J.*, 25, (3), pp. 436 -442.

H. F. Robey (1990), "Spectrum of a Passive Scalar in the Inertial-Convective Subrange of an Anisotropic Turbulent Flow", *Phys. Rev. Lett.*, 65, (20), pp. 1360-1363.

H. F. Robey, G. F. Albrecht, and T. R. Moore (1990), "An Optical Technique for the Direct Measurement of the 2-D Spectral Density of a Passive Scalar in a Turbulent Flow", *AIAA Paper 90-1667, AIAA 21<sup>st</sup> Fluid & Plasma Dynamics Conf.* Seattle, WA, 18-20 June.

D. A. Rotman (1991), "Shock Wave Effects on a Turbulent Flow", *Phys. Fluids, Ser. A*, 3, pp. 1792-1806.

N. F. Sather (1973), "Approximate Solutions of the Boltzmann Equation for Shock Waves", *Phys. Fluids*, 16, (12), 2106-2109.

N. F. Sather and C. J. Lin (1975), "Approximate Solutions of the Boltzmann Equation for Shock Waves, II", *Phys. Fluids*, 18, (1), 36-39.

A. M. Savill (1987), "Recent Developments in Rapid Distortion Theory", *Ann. Rev. Fluid Mech.* 19, Ann. Rev. Inc., Palo Alto, 531 -575.

G. S. Settles, J. J. Perkins, and S. M. Bogdonoff (1981), "Upstream Influence Scaling of 2D & 3D Shock/Turbulent Boundary Layer Interactions at Compression Corners", *AIAA Paper 81-0334*.

G. S. Settles, I. E. Vas, and S. M. Bogdonoff (1976), "Details of a Shock-Separated Turbulent Boundary Layer at a Compression Corner", *AIAA J.*, 14, (12), pp. 1709-1715.

G. S. Settles, T. J. Fitzpatrick, S. M. Bogdonoff (1979), "Detailed Study of Attached and Separated Compression Corner Flowfield in High Reynolds Number Supersonic Flow", *AIAA J.*, 17, pp. 579-585.

M. Shigemi, H. Koyama, Y. Aihara (1976), "A Note on the Oscillating Shock Wave - Some Experiments" *Trans. Japan Soc. Aero. & Space Sci.*, 19, p. 68.

A.J.Smits, K. Hayakawa, and K.- C. Muck (1983), "Constant Temperature Hot-Wire Anemometry Practice in Supersonic Flows, Part I: The Normal Wire" *Experiments in Fluids* 1, p. 83

A.J. Smits and K. - C. Muck (1984), "Constant Temperature Hot-Wire Anemometry Practice in Supersonic Flows, Part II: The Inclined Wire" *Experiments in Fluids*, 2, p. 33

**A-Program Hydrodynamics & Turbulence Theory & Simulation Effort**

Mail Station L-023;

Extension 34828; fax 30925 Email: alfredcb@llnl.gov

04/01/99

**MEMORANDUM**

Page 17

A. J. Smits and K.- C. Muck (1987), "Experimental Study of Three Shock Wave/Turbulent Boundary Layer Interactions", *J. Fluid Mech.*, 182, p. 291.

A. J. Smits (1988). "Lecture Series on Turbulence with Compressibility", *Proc. Summer Session, NASA-Ames/Stanford Univ. Center for Turbulence Research*.

A. J. Smits & J.-P. Dussauge (1996), *Turbulent Shear Layers in Supersonic Flow*, AIP Press, Woodbury, NY, pp. 94-95, 103-104.

C. G. Speziale, G. Erlebacher, T. A. Zang, and M. Y. Hussaini (1988), "The Subgrid Scale Modeling of Compressible Turbulence", *Phys. Fluids*, 31, 940-948.

B. Sturtevant (1977), "Shock Waves in Nonuniform Media: Real-Life Gasdynamics", *Shock Tube and Shock Wave Research*, Ahlborn, Hertzberg, Russell, eds. 12 – 23.

G. I. Taylor (1910), "The Conditions Necessary for Discontinuous Motion in Gases", *Proc. Royal Society A*, 84, pp. 371-377.

G. I. Taylor (1935), *Z. Angew. Math. Mech.* 15, 91.

A. A. Townsend (1970), "Entrainment and the Structure of Turbulent Flow", *J. Fluid Mech.* 41, 13-46.

A. A. Townsend (1976), *The Structure of Turbulent Shear Flow*, 2<sup>nd</sup> Edition, Cambridge University Press, Cambridge.

A. A. Townsend (1980), "The Response of Sheared Turbulence to Additional Distortion", *J. Fluid Mech.* 98, 171 – 191.

J. W. Troler (1984), "Turbulence Measurements in Shock Induced Flows," *Ph.D. Thesis*, Rennselaer Polytechnic Institute, Troy NY.

J. W. Troler and R. E. Duffy (1985), "Turbulence Measurements in Shock- Induced Flows", *AIAA J.* 23, p. 1172.

T. A. Zang, D. A. Kopriva, and M. Y. Hussaini (1983), "Pseudospectral calculations of Shock Turbulence Interactions", *Numerical Methods in Laminar and Turbulent Flow*, ed. C. E. Taylor, Pineridge Press, Swansea, UK.

T. A. Zang, M. Y. Hussaini, and D. M. Bushnell (1984), "Numerical Computation of Turbulence Amplification in Shock Wave Interactions", *AIAA J.* 22, 13-20.

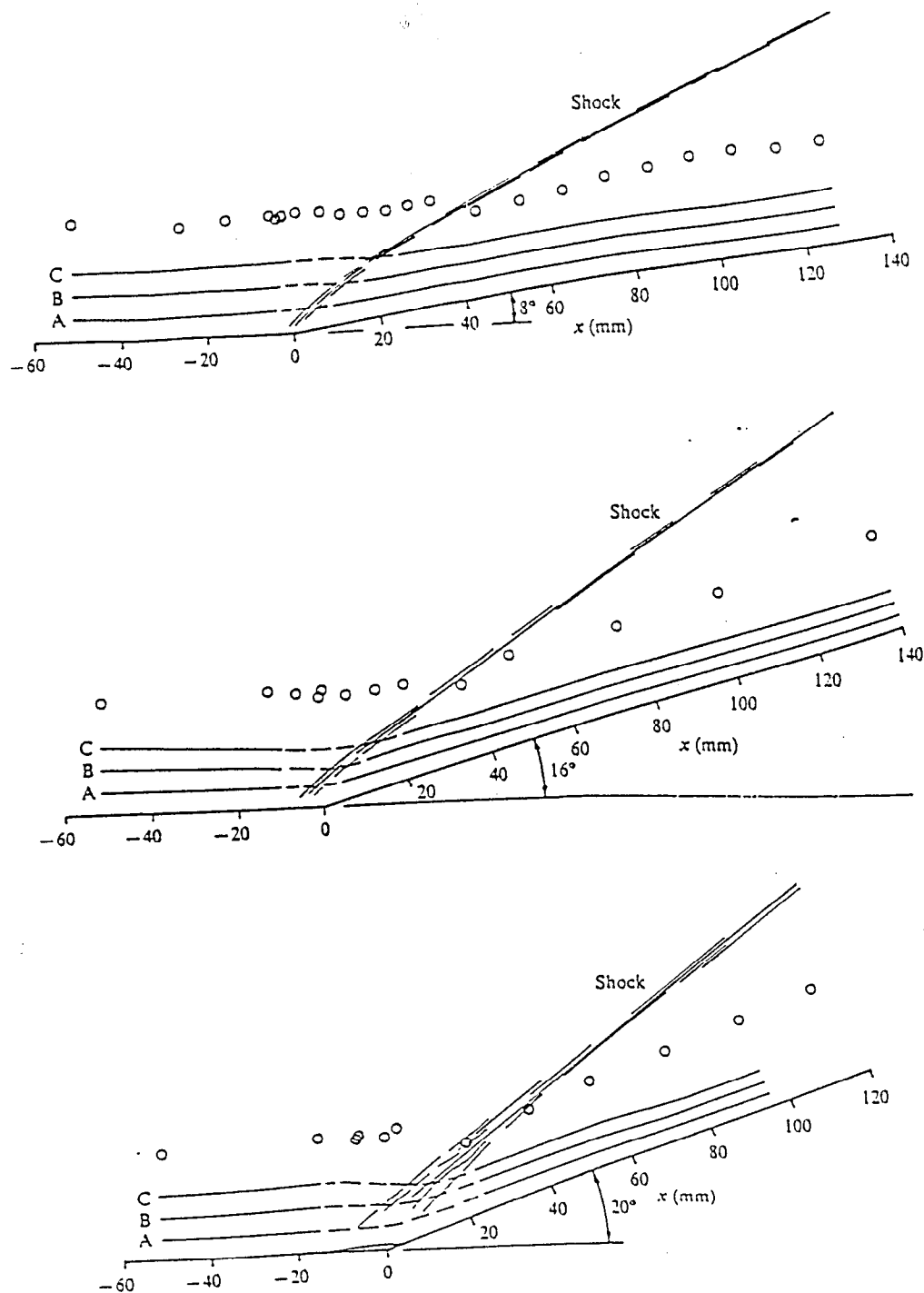


Figure 1. Shock boundary layer interaction on 8°, 16°, and 20° (top to bottom) wedge compression corners. Lines A, B, and C are traces of streamlines displaced from the surface by  $y/\delta = 0.2, 0.4,$  and  $0.6$ , respectively;  $\delta$  = boundary layer thickness; shadowgraph tracing from Smits and Muck (1987).

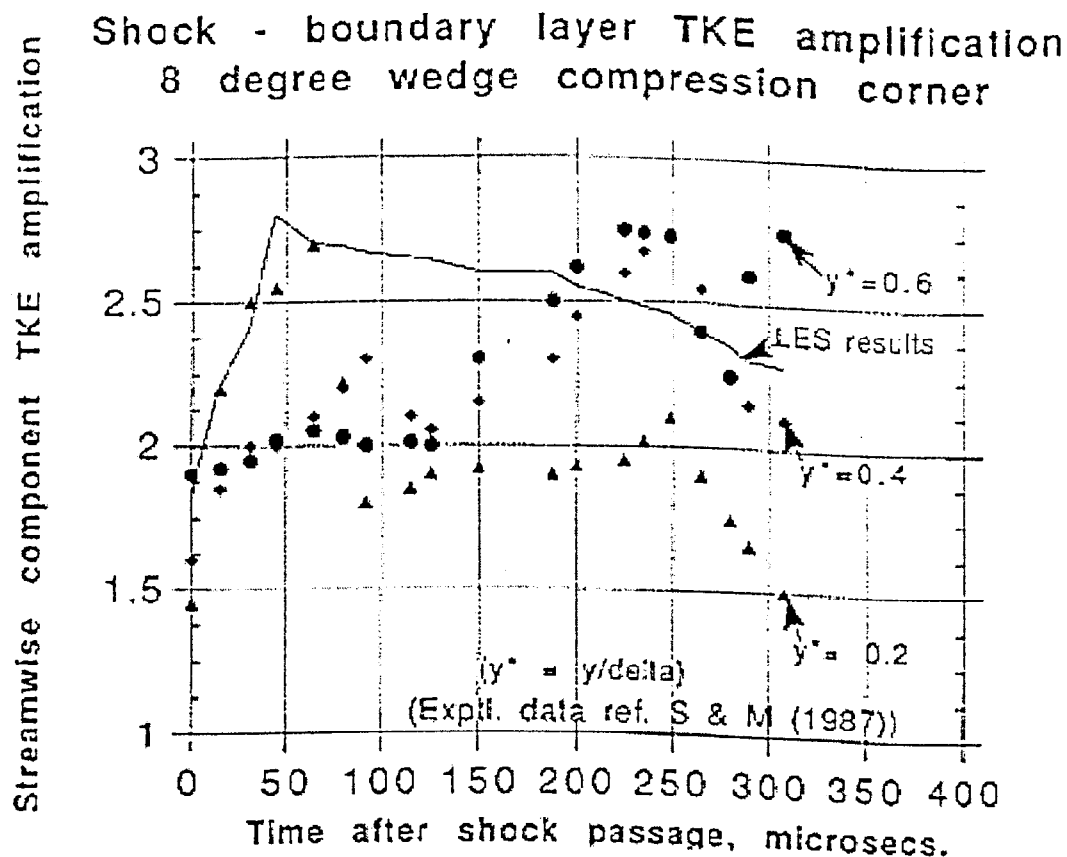


Figure 2. Shock boundary layer interaction on 8° wedge compression corner; amplification of streamwise turbulent kinetic energy for 3 experimental streamline displacements from Smits and Muck (1987); comparison with near surface resolved LES results from Buckingham and Grun (1993a).

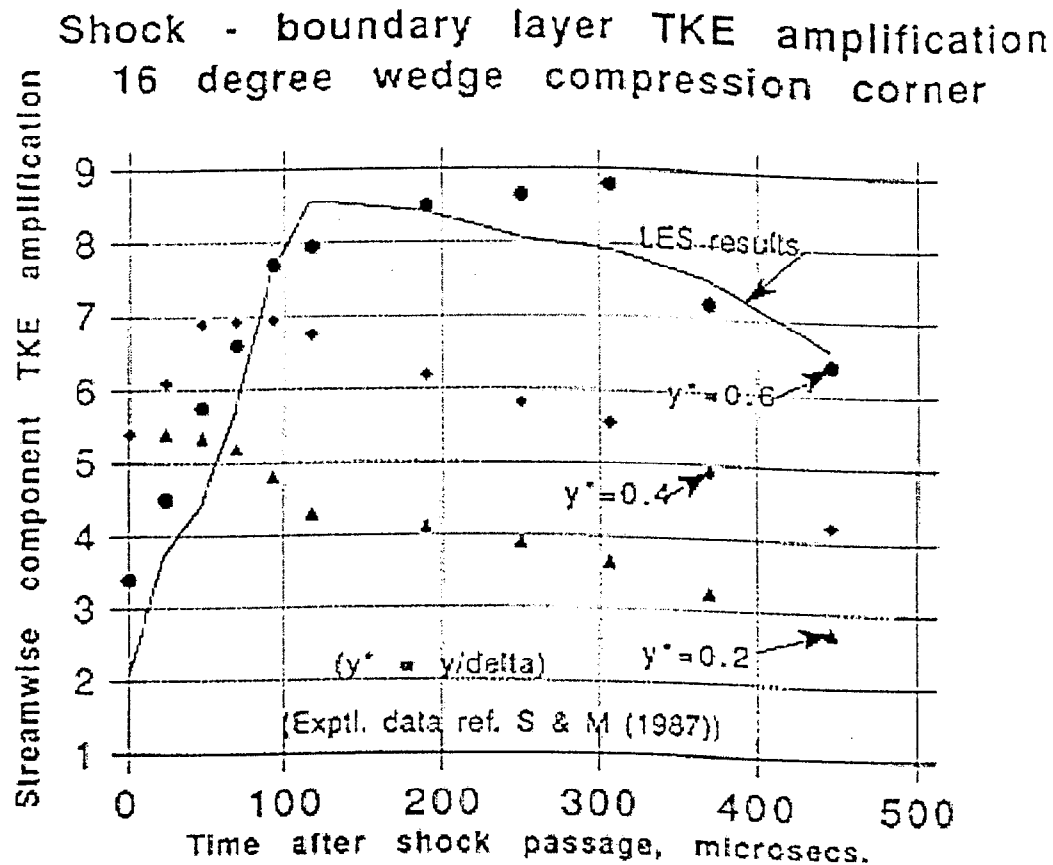


Figure 3. Shock boundary layer interaction on 16° wedge compression corner; amplification of streamwise turbulent kinetic energy for 3 experimental streamline displacements from Smits and Muck (1987); comparison with near surface resolved LES results from Buckingham and Grun (1993a).

12/16/98

Page 10 of 21

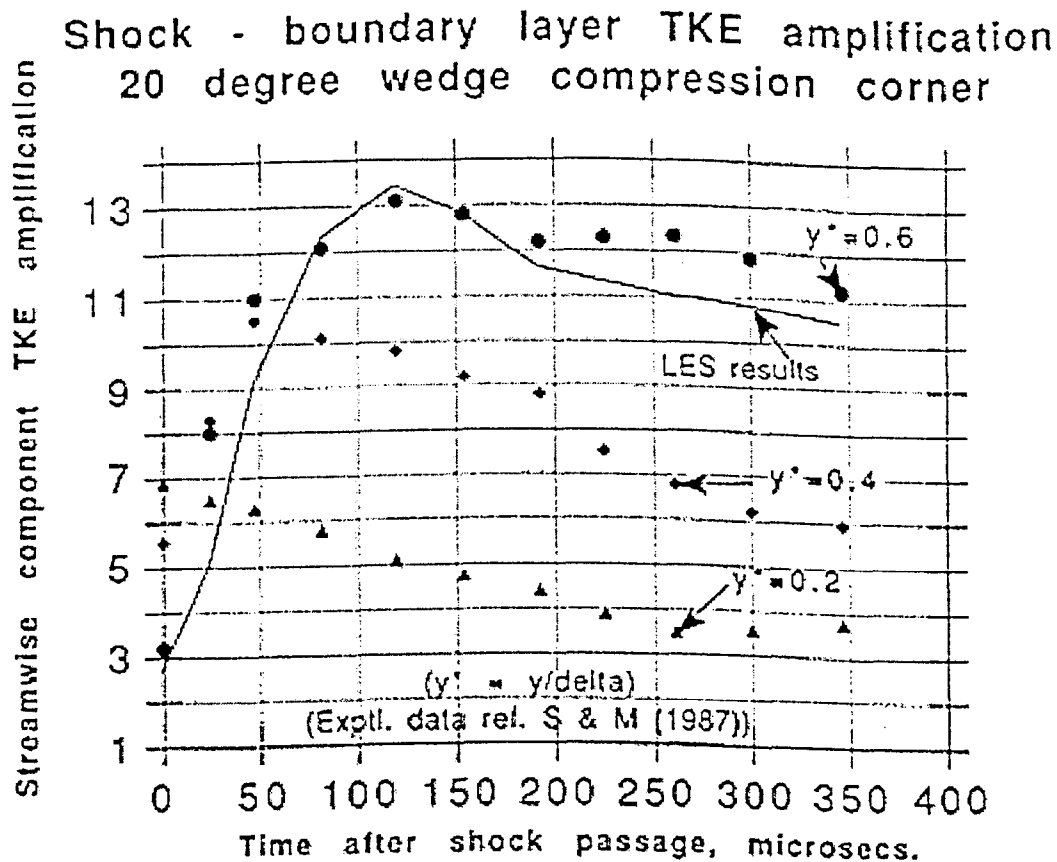


Figure 4. Shock boundary layer interaction on 20° wedge compression corner; amplification of streamwise turbulent kinetic energy for 3 experimental streamline displacements from Smits and Muck (1987); comparison with near surface resolved LES results from Buckingham and Grun 1993a).

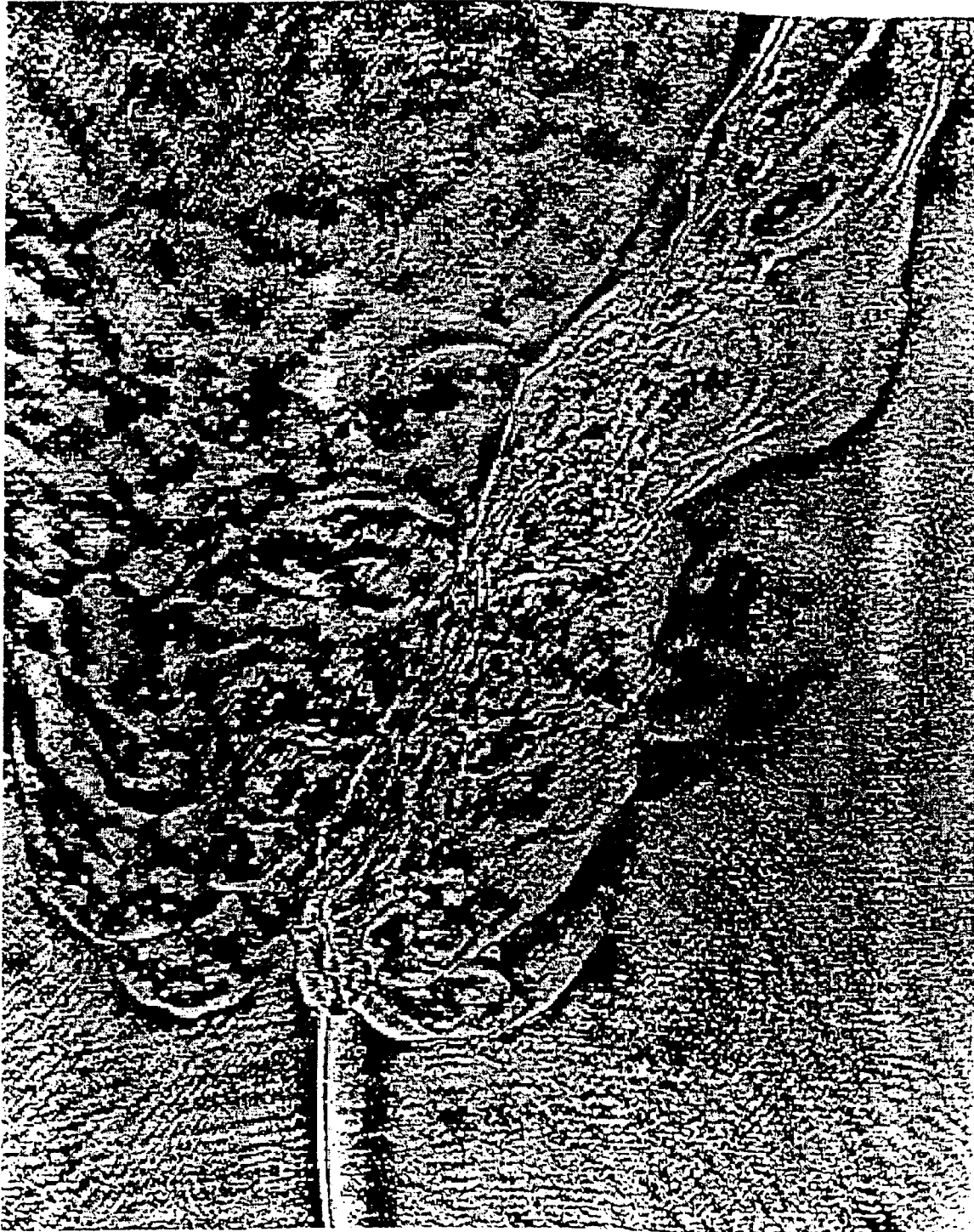


Figure 5. Hypersonic (Mach No.  $\approx 100$ ) shock turbulence interaction experiments. Turbulent plume of pulsed laser vaporized Al target in upper left corner interacts with cylindrical hypersonic ablation relief shock driven by a second laser target pulsed interaction. The shock is seen moving from right to left in this phase contrast schlieren photo image. Sharp shock front at lower left is seen to be seriously distorted by interaction with the turbulent plume at the top of the photograph; experiments of Grun et al (1992).

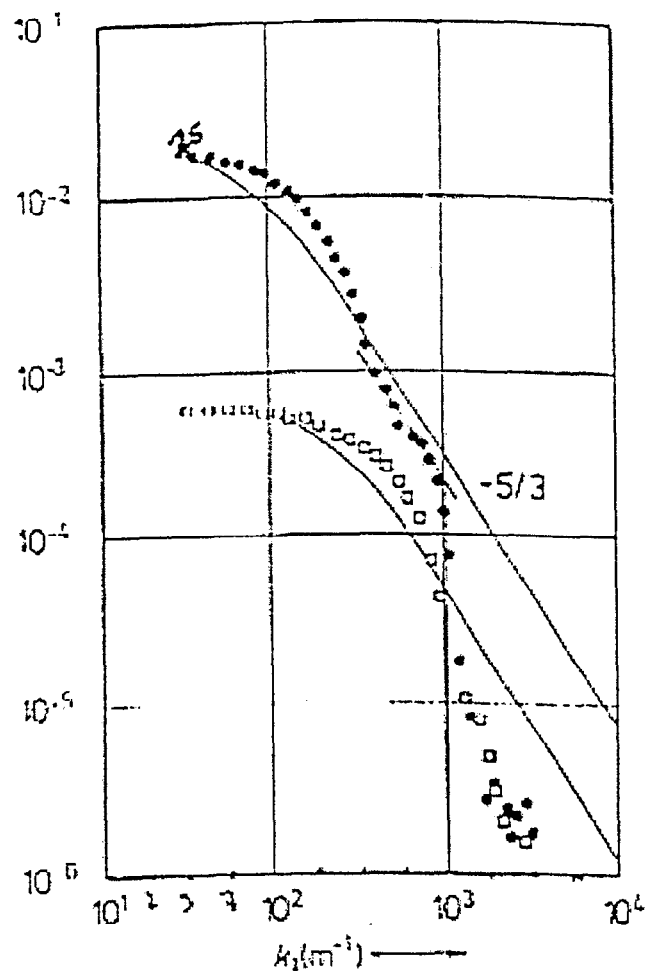


Figure 6. Shock tube generated grid turbulence one dimensional energy spectrum  $E_{1T}$  as a function of wave number  $k_1$ ; grid spacing (M) based  $Re = 35,000$ ; --- Kolmogorov theory; experiment:  $\square$  before interaction,  $\bullet$  after interaction with shock wave. From Honkan and Andreopoulos (1992).

MEMORANDUM

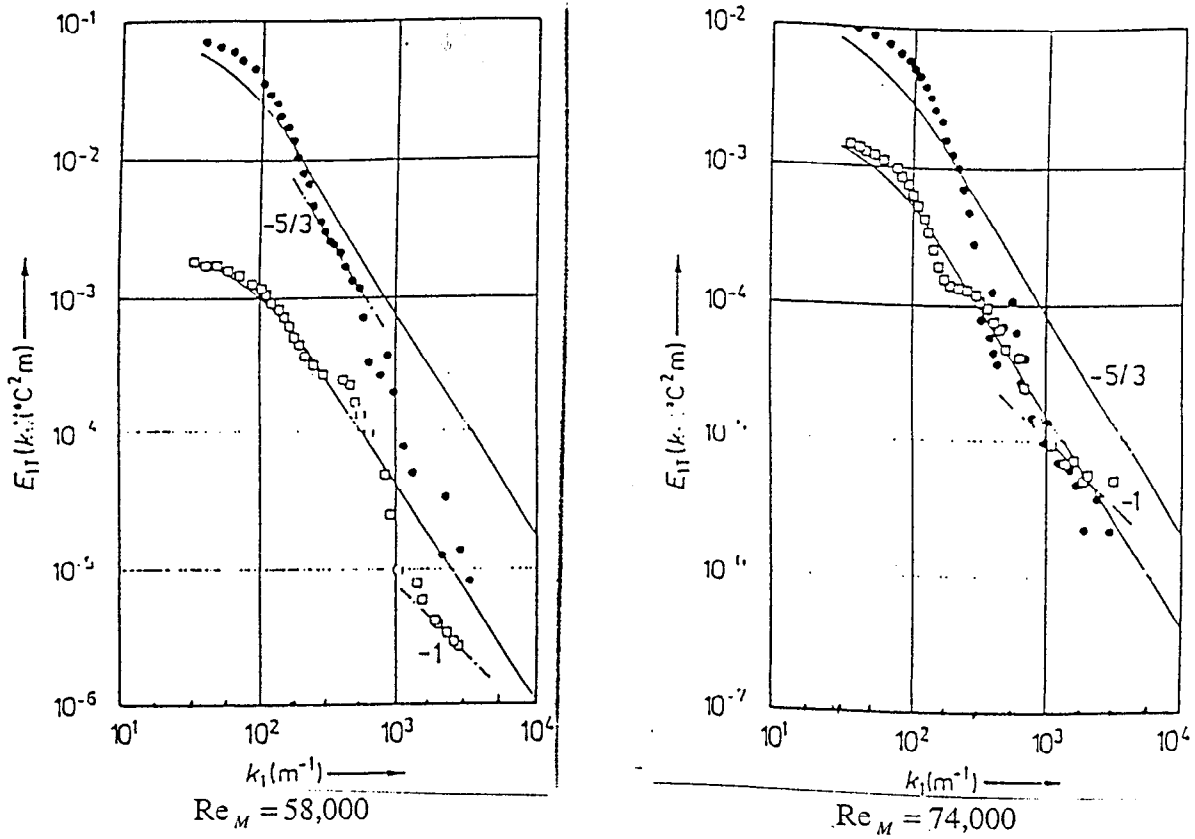
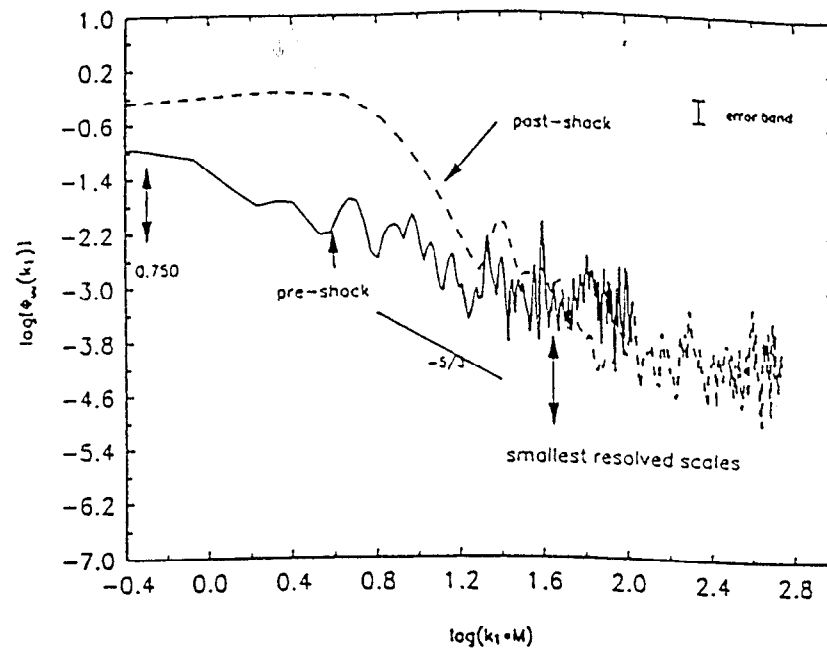


Figure 7. Shock tube generated grid turbulence one dimensional energy spectrum  $E_{1T}$  as a function of wave number  $k_1$ ; grid spacing (M) based  $Re = 58,000$  (left figure) and  $74,000$  (right figure); — Kolmogorov theory; experiment:  $\square$  before interaction,  $\bullet$  after interaction with shock wave. From Honkan and Andreopoulos (1992).



One-dimensional wave-number spectra

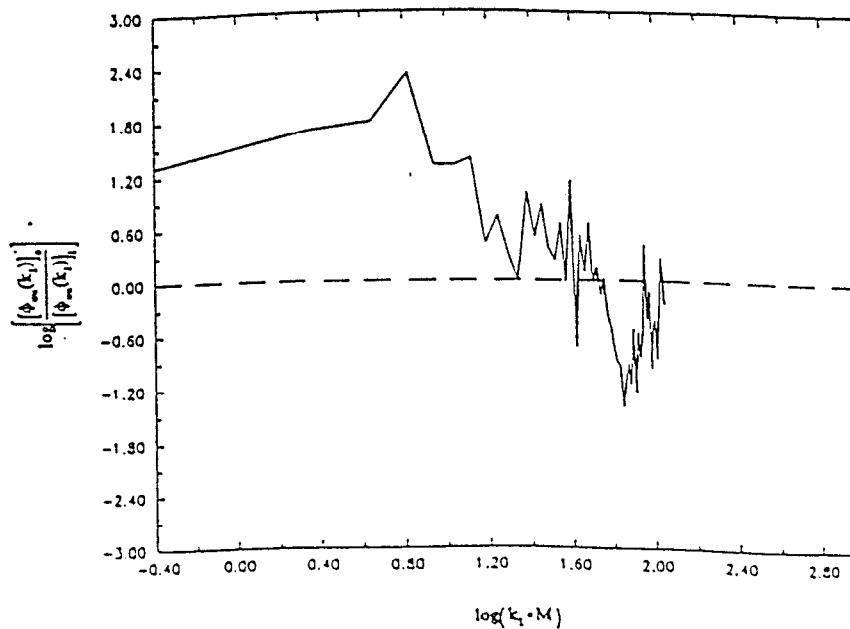
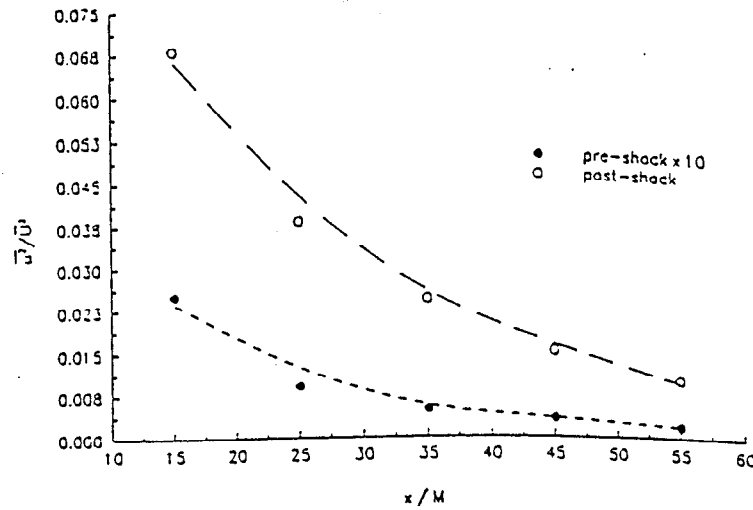


Figure 8. (Top figure) One dimensional turbulent intensity wave number spectra: \_\_\_\_\_ before interaction, \_\_\_\_\_ after interaction with shock wave. From Honkan and Andreopoulos (1992). (Bottom figure) Shock amplification of one dimensional turbulent intensity as a function of dimensionless wave number,  $k_1 \cdot M$ , where  $M$  is the grid spacing for the grid generated turbulence. From Honkan and Andreopoulos (1992).



Decaying turbulence: ● , before shock; ○ , after shock.

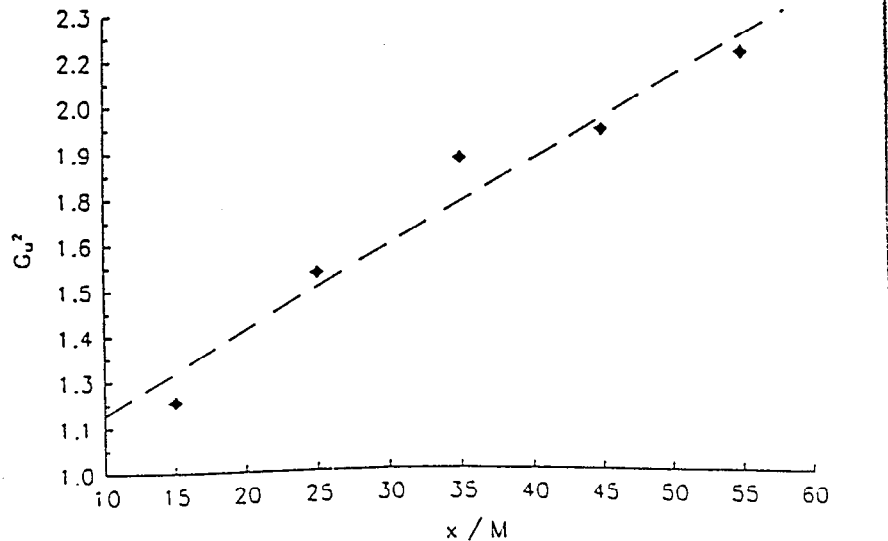


Figure 9. (Top figure) Decay of one-dimensional grid generated turbulence kinetic energy with dimensionless distance,  $x/M$  behind grid, where  $M$  = grid mesh spacing; \_\_\_\_\_ before interaction, \_\_\_\_\_ after interaction with shock wave. (Bottom figure) Shock amplification of one-dimensional grid generated turbulence with dimensionless distance,  $x/M$  behind grid, where  $M$  = grid mesh spacing. From Honkan and Andreopoulos (1992).

# A-Program Hydrodynamics & Turbulence Theory & Simulation Effort

Mail Station L-023;

Extension 34828; fax 30925

Email: alfredcb@llnl.gov

04/01/99

## MEMORANDUM

### Distribution

Albrecht, Georg  
Amala, Paul  
Anderson, Charles  
Bauer, Joseph  
Benjamin, Russell  
Bolstad, John  
Buckingham, Alfred  
Burke, Eugene  
Carman, Scott  
Castor, John  
Cheng, Kwok-Tsang  
Cloutman, Lawrence  
Cohen, Ronald  
Cook, Andrew  
Cook, Grant  
Dalhed, Sam  
Dannevik, William  
Dearborn, David  
Dimits, Andris  
Dimonte, Guy  
Dittrich, Tom  
Dykema, Pieter  
Eliason, Donald  
Farley, David  
Greenough, Jeff  
Haan, Steve  
Harding, Rollin  
Hoover, Todd  
Klein, Richard  
Klem, Dan  
Kraybill, David  
Kuhl, Alan  
Leith, Chuck

Libby, Stephen  
Miller, Paul  
Mirin, Arthur  
Moore, Roger  
Moreno, Juan  
Murray, Stephen  
Mustafa, Mohammed  
Nash, Jeffrey  
Nilsen, Joseph  
Nowak, Paul  
O'Brien, Hank  
Perry, Theodore  
Post, Douglass  
Rambo, Peter  
Ramshaw, John  
Rathkopf, James  
Remington, Bruce  
Robey, Harry  
Schilling, Oleg  
Shepard, Thomas  
Smith, Donald  
Snyderman, Neal  
Stanfel, David  
Stry, Peter  
Thomson, Thomas  
Tipton, Robert  
Verdon, Charlie  
Wan, Alan  
Ward, David  
Weber, Steven  
Wheeler, Paul  
Wojtowicz, Deborah